EFFECTS OF PEDESTRIAN SYNCHRONISATION ON UNDER-DECK CABLE-STAYED FOOTBRIDGES

Georgiadis Konstantinos[*, a], Ana M. Ruiz-Teran[b], Peter J. Stafford[c]

[a] PhD Candidate. Imperial College. Faculty of Civil and Environmental Engineering. London UK

[b] Doctor Ingenico de Ceminos, Canales y Puertos, Senior Lecturer in Bridge Engineering. Imperial College. Faculty of Civil and Environmental Engineering. London UK

[c] PhD, MEng Civil Engineering, Reader in Engineering Seismology & Earthquake Engineering. Imperial College. Faculty of Civil and Environmental Engineering. London UK

ABSTRACT

Under-deck cable-stayed (UDCS) footbridges are slender structures supported by stay-cables located below the deck and possess a number of advantages such as high structural efficiency and sustainability, due to the small amount of materials. However, due to their slenderness they become more prone to vibrations induced by pedestrians. In the present work, the dynamic response of a benchmark UDCS footbridge has been investigated, considering a stochastic representation of the pedestrian loading. The effects of synchronisation of pedestrian step frequency to different lateral and torsional modes of the bridge have been examined. Results show that although synchronisation with certain modes can increase vibrations does not lead to dynamic instability.

KEYWORDS: dynamic, lock-in, pedestrian actions, synchronous lateral excitation, vibrations

1. Introduction

Under-deck cable-stayed (UDCS) footbridges are slender structures supported by prestressed cables located underneath the deck and deviated with the aid of struts (see Figure 1). The cables are under tension, the struts are under compression, whereas the deck under compression and bending moment.

These bridges possess a number of advantages such as high structural efficiency, sustainability due to the small amount of materials, multiple construction possibilities and strong aesthetic characteristics. Therefore, they consist an attractive proposal for covering medium spans in the modern urban and rural environment. However, due to their slenderness they become more prone to vibrations that can be excited by pedestrian actions.

Realistic representation of dynamic pedestrian actions is a very sophisticated task that involves a lot of uncertainty due to the stochastic nature of human behaviour. Failures at serviceability of London Millennium Bridge in the UK, Solferino Bridge in France or Toda Bridge in Japan due to extensive vibrations indicate that until recently fundamental assumptions of pedestrian actions were misrepresented and the understanding of certain phenomena was limited or non-existed. These failures triggered a vast research aiming to a deeper investigation of the nature of pedestrian actions as well as their interaction with the vibrating bridge. Although there is still no clear agreement among researchers, synchronous lateral excitation (SLE) or lock-in effect, seems to be the main reasons for these serviceability failures.

Therefore, although in previous work carried out by the authors, the dynamic behaviour of UDCS footbridges under the action of a stochastic pedestrian load model has been examined [2], the present work focuses more on investigating the possibility and effects of SLE. A brief review of the dynamic effects of pedestrians on slender footbridges is presented first, followed by the research methodology. The acceleration response predicted by the applied pedestrian load model and a detailed investigation of SLE is discussed next. Finally, accelerations predicted by current design guidelines [3] have been obtained and compared with that of the applied pedestrian model (including and excluding SLE) for assessing users' comfort.

2. Dynamic effects of pedestrians on slender footbridges

Pedestrians crossing a footbridge introduce vertical, lateral and longitudinal actions on the bridge's deck. As the bridge's slenderness increases mass reduces, and therefore these actions can cause significant vibrations due the lightweight and the small damping of the bridge. Moreover, by increasing slenderness, the natural frequencies of the bridge become closer to the usual walking pedestrian step frequency and therefore, vibrations can be amplified due to resonance. Apart from the induced actions, the presence of pedestrians on slender footbridges also affects the mass, the stiffness and the damping of the combined pedestrian-structure system.

The dynamic effects of pedestrians are not independent from the vibrations of the bridge. Pedestrians introduce dynamic actions to the bridge and as a result, the bridge vibrates. The vibrations of the bridge are then received by them who are affected (if the vibrations are above a limit) and adopt their gait. Therefore, the transmitted actions and the influence on the properties of structure is different for a moving and a fix system. This interaction mechanism is called pedestrian-structure (or human-structure) interaction and its significance is different in the vertical and the lateral direction.

In the vertical direction, pedestrians are more stable as their legs provide an amount of damping, and consequently the movement of the structure has minor influence on their gait. Minimal differences on vertical actions between fixed and moving platforms have been observed experimentally by [4].

On the other hand, pedestrians are less stable in the lateral direction and therefore even small lateral movements 2 - 3 mm [5] or 0.10 - 0.15 m/s^2 [6] can affect their gait. Although a lot of research has been conducted to investigate the human balancing mechanism i.e. [7, 8] there is still no clear agreement among researchers (as each individual may act differently). Nevertheless, most researchers suggest that the initial balancing mechanism for pedestrians is to change their step width (foot position), whereas if vibrations increase, pedestrians change their step frequency in order to balance and become synchronised with the movement of the bridge.

This phenomenon is called synchronous lateral excitation (SLE), or lock-in effect, and despite the small amplitude of the later loads compared to that of vertical, can lead to lateral dynamic instability (i.e. London Millennium Bridge). This yields from the fact that, as the accelerations increase, more people become synchronised with the bridge in order to balance, increasing further the vibrations. Nevertheless, when lateral acceleration reach a certain limit (around 1.35 m/s^2) pedestrians can no longer walk, ceasing the oscillation of the bridge [9].

In order to take into account pedestrian-structure interaction as well as SLE, different approaches have been proposed in the literature. In order to simulate the pedestrian-structure interaction in the lateral direction, [10] suggested to use the inverted pendulum (IP) model. According to this model, pedestrian's balance is guaranteed in every step by the placement of the foot laterally according to the displacement and velocity of the centre of mass from the previous step. Nevertheless, the IP model does not cover situations where pedestrians have to adopt their step frequency and become synchronised with the bridge (SLE). In order to account for SLE, [11] proposed an equation to calculate the critical number of people that could cause lateral dynamic instability based on the characteristics of the bridge and assuming that pedestrians are uniformly distributed along its length. Finally, [3] advises to limit lateral acceleration to around 0.10 - 0.15 m/s^2 in order to prevent SLE.

3. Research methodology

For investigating the dynamic behaviour of UDCS footbridges and the effects of SLE, a benchmark bridge configuration, representative for this typology, has been first selected (see Figure 2).

For the simulation and analysis of the benchmark bridge, a three dimensional finite element (FE) model has been developed in ABAQUS. Shell elements (S4R) have been used for the concrete slab, beam elements (B31) for the steel girders and the struts, and truss elements (T3D2) for the cables. More details about geometrical and mechanical characteristics as well as the FE model of the benchmark bridge can be found in [2].

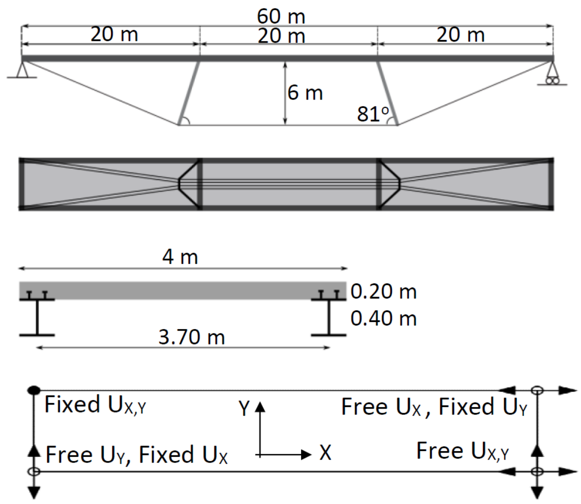

Figure 2. Geometrical configuration of the benchmark bridge and bearing articulation [2].

For predicting the dynamic response of the bridge, implicit dynamic analysis including geometric non-linearity under the action of a stochastic pedestrian load model as described in [2], has been performed in ABAQUS. This model, considers different loading scenarios (pedestrian densities, aims journey) and simulates the actions introduced by individual pedestrians (with different anthropometric characteristics), inter- and intra-variability, as well as pedestrian-structure and pedestrian-pedestrian interaction (see Figure 3).

During the simulation, pedestrians are generated, according to Poisson arrival, with a random initial position uniform distributed along the width of the bridge and a desired destination on the other side of the bridge. Each pedestrians has different anthropometric characteristics (gender, age and height). The Social Force Model proposed by [12] has been implemented in order to simulate the crowd interaction whereas Metropolis-Hastings algorithms have been considered to account for intra-variability of the step frequency.

In order to consider the effects of SLE in the dynamic response of the bridge, different percentages of synchronised pedestrians (with lateral and torsional modes) have been examined.

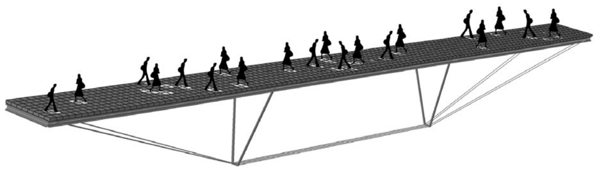

Figure 3. Representation of the stochastic pedestrian load model for the dynamic analysis of the benchmark bridge in ABAQUS.

Peak and RMS_{1sec} accelerations along the bridge have been obtained. As the implemented pedestrian load model follows a stochastic approach, ten simulations for each loading scenario have been performed reporting the mean value of accelerations and the corresponding error for 95% confidence intervals. Actual acceleration felt by pedestrians while crossing the have also been obtained expressed in statistical terms [13]. Finally, accelerations predicted by current design guidelines [3] have been calculated and compared with that of the stochastic pedestrian load model. For appraising comfort, accelerations have been evaluated against comfort limits proposed in the literature [3].

4. Accelerations predicted by the stochastic pedestrian model

Different loading scenarios (pedestrian densities and aims of journey) have been considered for the dynamic analysis of the benchmark bridge (see Table 1). From these, medium pedestrian density (0.6 ped/m^2) for Leisure activities was found the most critical. This yields from the fact that the mean pedestrian step frequency for those conditions, as derived from the implemented pedestrian load model, is closer to the structural frequencies of third flexural mode V3 and the first torsional mode T1 amplifying the dynamic response due to resonance (see Figure 4). The high contribution of the V3 and T1 mode in the vertical and lateral direction has been previously confirmed from the response of the bridge in the frequency domain [2].

Table 1. Pedestrian loading scenarios.

	Aim of journey		
	Business	Commuting	Leisure
Density (ped/m^2)	0.2	0.2	0.2
	0.6	0.6	0.6
	1.0	1.0	1.0

In the vertical direction, due to the contribution of torsional modes, peak and RMS_{1sec} accelerations have been plotted along the edge line (after extracting the width of the parapet) of the bridge (see Figure 5). On the other hand, in the lateral direction due to the high stiffness of the deck (working as diaphragm), accelerations are uniform across the width, and they have been plotted along the central line of the bridge (see Figure 6).

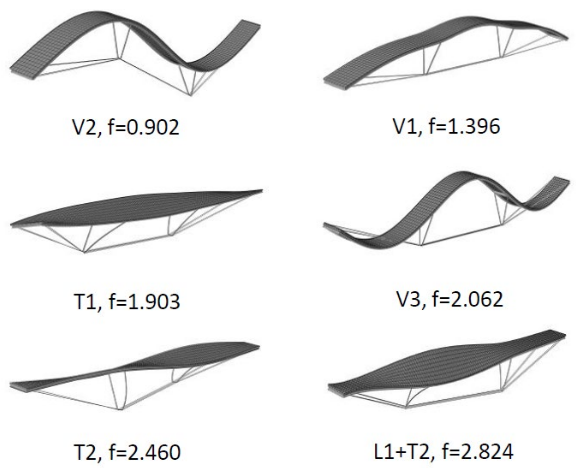

Figure 4. Mode shapes and frequencies (in Hz) of the benchmark bridge, with the first letter indicating the mode direction (V for vertical; L for lateral; T for torsional) and the following number indicating the number of waves in that direction [2].

In the vertical direction, peak accelerations along the bridge length follow the shape of the third flexural mode V3 with maximum values of around 1.55 m/s^2 at its antinodes. RMS_{1sec} accelerations follow the same shape, but are around 40% smaller. In the lateral direction, peak accelerations follow the shape of the first torsional mode T1 with maximum values of around 0.35 m/s^2 at the mid-span. RMS_{1sec} accelerations drop to around 0.20 m/s^2.

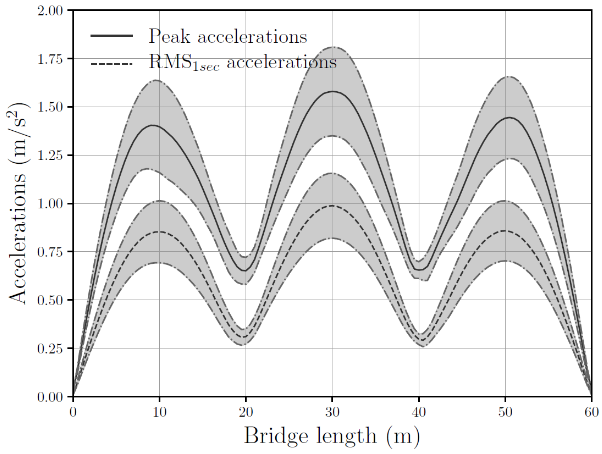

Figure 5. Mean value and error of vertical peak and RMS_{1sec} accelerations along the bridge [2].

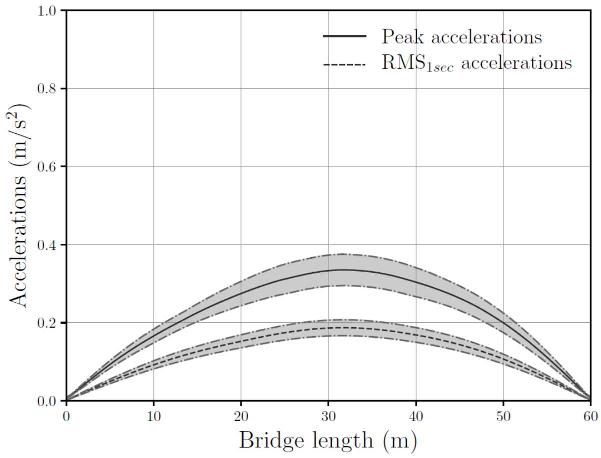

Figure 6. Mean value and error of lateral peak and RMS_{1sec} accelerations along the bridge [2].

The significant reduction in the response observed from peak to RMS_{1sec} accelerations suggests that reporting only peak values may be over conservative for assessing comfort. Therefore, in order to find the concurrence of peak accelerations with time, accelerations along the bridge length have been plotted over the total simulation time after ten simulations (see Figure 7 and 8). Along the whole bride for about 90% of the total simulation time the peak vertical accelerations do not exceed 1.00 m/s^2 whereas the peak lateral do not exceed 0.20 m/s^2. Interestingly, these values are very close to RMS_{1sec} accelerations.

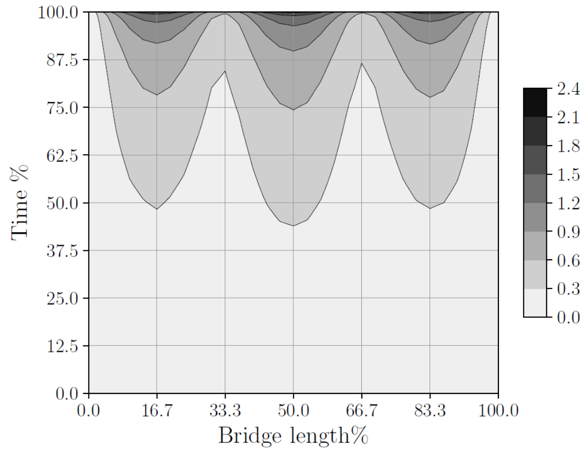

Figure 7. Distribution of vertical accelerations (m/s²) over time after ten simulations.

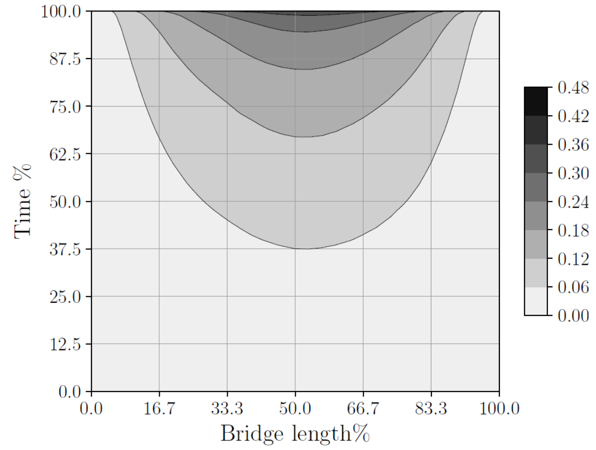

Figure 8. Distribution of lateral accelerations (m/s²) over time after ten simulations.

As from the stochastic pedestrian load model the positions and times of footsteps of each pedestrian while crossing the bridge are known, the actual accelerations felt by pedestrians while crossing the bridge have been obtained and expressed in statistical terms. Figure 9 and 10 shows the mean values and the corresponding error after ten simulations, as well as accumulated acceleration felt by pedestrians from all simulations.

The maximum peak accelerations have been felt by a very small fraction of pedestrians (or by anyone if they happen in a location without pedestrians) and therefore it is over conservative to use that criterion for appraising comfort for the bridge users. Accelerations felt by 50% of pedestrians (comfort limits usually correspond to acceptable vibrations by 50% of the population) are around 0.90 m/s^2 in the vertical and 0.20 m/s^2 in the lateral direction. Interestingly, these values are also very similar to RMS_{1sec} accelerations.

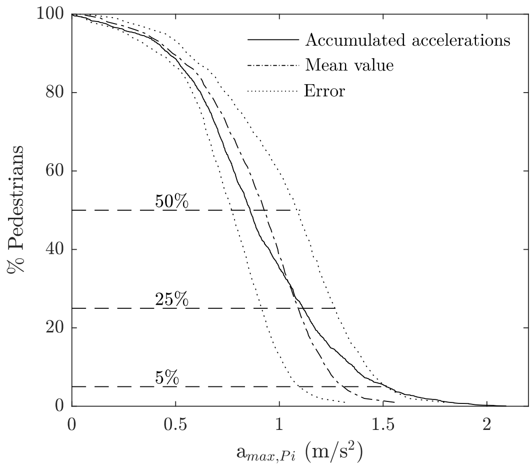

Figure 9. Accumulated accelerations and mean value of accelerations felt by pedestrians after ten simulations in the vertical direction.

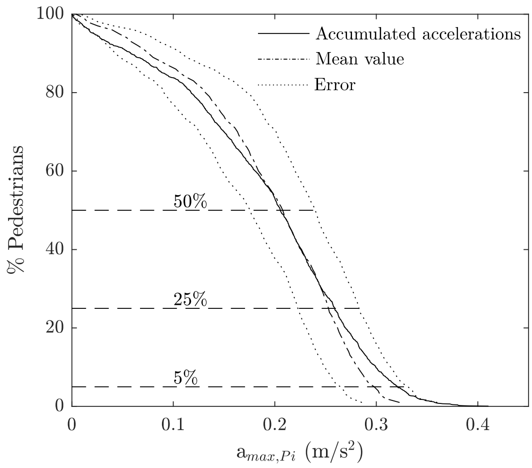

Figure 10. Accumulated accelerations and mean value of accelerations felt by pedestrians after ten simulations in the lateral direction.

5. Consideration of SLE

The accelerations presented in the previous section, have been obtained without considering SLE. As it was discussed before, if lateral accelerations are above a threshold of 0.10 - 0.15 m/s^2 pedestrians tend to change their step frequency and become synchronised with the movement of the bridge. However, it has been suggested that this synchronization is only possible for bridges with lateral frequencies less than 1.30 - 1.50 Hz [3, 4, 11] as the lateral pedestrian step frequency (which is half from the vertical) cannot exceed that limit for normal/fast walking.

For the bridge under examination, the first lateral mode appears combined with the second torsional mode (L1+T2) and has a frequency of around 2.53 - 2.60 Hz depending on the pedestrian density. These values are well above the maximum lateral frequency limit for triggering SLE proposed in the literature and therefore the risk of lock-in seems unlikely.

Nevertheless, even though synchronisation with the L1+T2 mode cannot occur (as pedestrians should walk with a vertical frequency around 5.20 Hz) synchronisation with the closest possible fraction of its frequency (2/3 which yields to a vertical pedestrian frequency of around 1.73 Hz) has been examined.

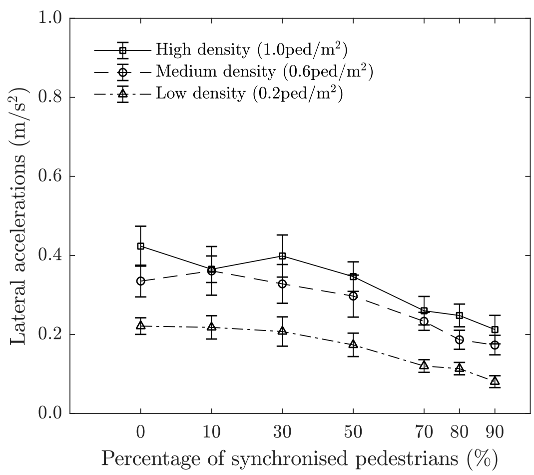

Figure 11. Peak lateral accelerations for different percentages of synchronised pedestrians with L1+T2 mode.

Figures 11 and 12 show the peak lateral and vertical accelerations of the bridge for different percentages of synchronised (in frequency and phase) pedestrians for different pedestrian densities. Synchronisation with that fraction of the lateral frequency is not critical and generally reduces the acceleration response as the level of synchronisation increases. The more pedestrians are forced to walk with frequency of 1.73 Hz, the less excite the dominant modes V3 and T1 (with frequencies in the proximity of 2

Hz) and therefore the acceleration response is improved.

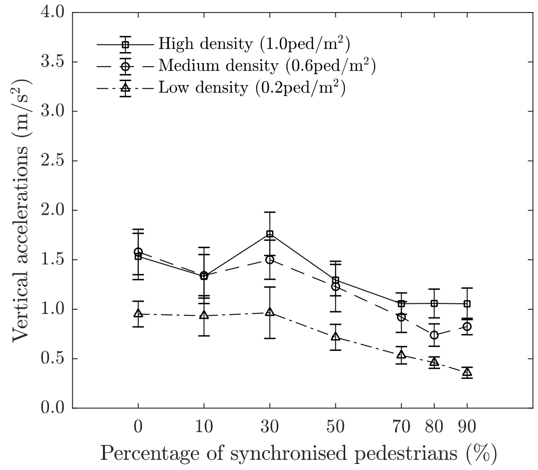

Figure 12. Peak vertical accelerations for different percentages of synchronised pedestrians with L1+T2 mode.

Although it has been suggested that synchronisation does not seem to occur for torsional modes [3], synchronisation with the first torsional mode T1 which is in the proximity of the mean walking frequency and has the main contribution in the lateral accelerations has also been examined (see Figure 13 and 14).

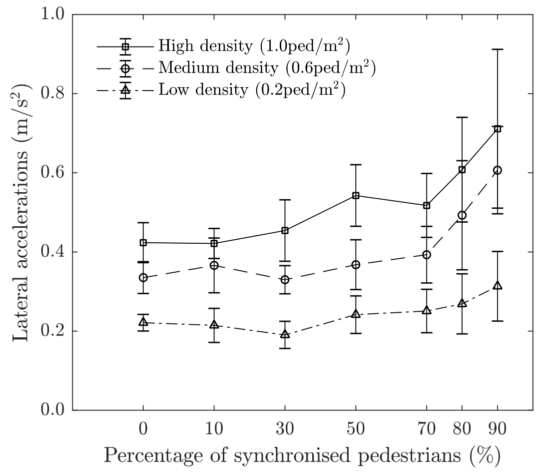

Figure 13. Peak lateral accelerations for different percentages of synchronised pedestrians with T1 mode.

In the lateral direction, no significant change in accelerations is recorded with synchronisation up to 30% for all pedestrian densities. A slight increase is observed from 30% to 70% synchronisation, whereas a more steep increase (especially for medium and high density) is observed above 70%.

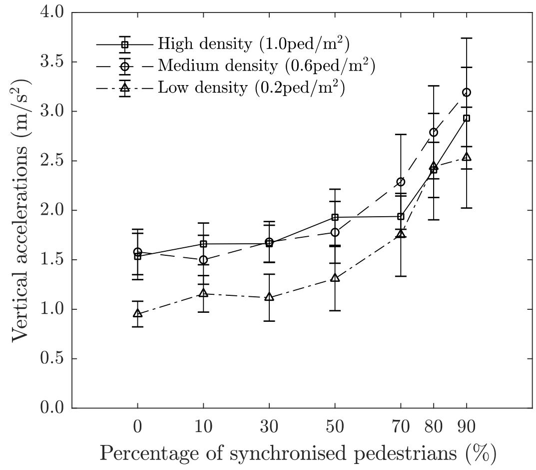

Figure 14. Peak vertical accelerations for different percentages of synchronised pedestrians with T1 mode.

In the vertical direction, a small increase in accelerations is observed with synchronisation up to 50% for all pedestrian densities, whereas a more rapid increase is recorded above that limit. The considerable increase of the vertical accelerations due to the synchronisation with the torsional mode T1 is attributed on the one hand to the high contribution of this mode in the vertical accelerations and on the other to the close proximity of its frequencies with that of the third flexural mode V3.

In the literature, the percentage of synchronised pedestrians with the bridge vibrations (accelerations or displacements) varies. From full-scale experiments in Solferino bridge the percentage to synchronised pedestrians reached up to 60% when the threshold acceleration of 0.10 m/s^2 was exceeded [3]. Based on that, synchronisation up to 60% with the first torsional mode T1, has been considered realistic to review the possible effects of SLE in the comfort appraisal of the bridge (see Section 7). Nevertheless, it should be mentioned that even for 90% synchronisation, although both vertical and lateral accelerations increase, no dynamic instability occurs.

6. Accelerations predicted by design guidelines

Setra [3] is one of the most well established and widely used design guidelines for dynamic assessment of footbridges, and therefore it has been used for comparing the accelerations predicted by the stochastic pedestrian load model. It takes into account the different levels of pedestrian density but does not considered other factors that affect human walking (i.e. anthropometric characteristics or aim of journey). To calculate the maximum accelerations from a stream of randomly walking pedestrians it converts them to an equivalent number of perfectly synchronised and equally distributed pedestrians, with sign related to the sign of the most critical mode (see Figure 15).

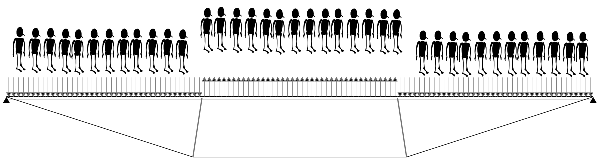

Figure 15. Applied load according to [3].

In the vertical direction, the third flexural mode V3 was found the most critical as produces the highest level of accelerations. Figure 16 shows the vertical accelerations along the bridge for different pedestrian densities. For low (0.2 ped/m^2) and medium (0.6 ped/m^2) density, accelerations are about 20% and 30% higher compared to that predicted from the stochastic pedestrian load model. However, for high pedestrian density (1.0 ped/m^2) an unrealistically high value of 6.2 m/s^2 is provided by [3].

In the lateral direction according to [3], the frequency of the bridge falls outside of the range of the critical frequencies, and therefore no lateral load need to be introduced. However, ignoring the lateral direction is not conservative as significant lateral accelerations can be produced form the high contribution of the first torsional mode T1 and can be further increased by considering SLE as it was shown before.

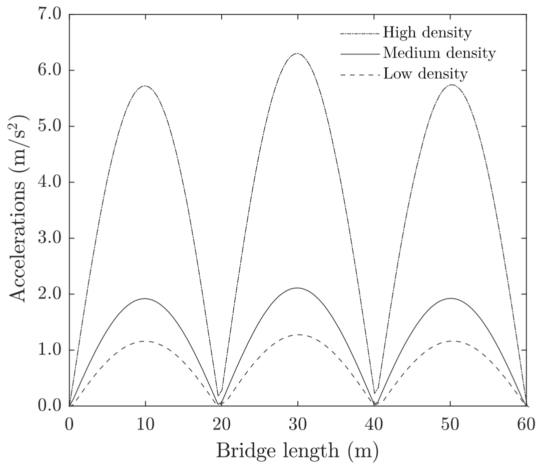

Figure 16. Vertical peak accelerations along the bridge according to [3].

Based on the above it can be concluded, the current design practice for predicting accelerations can be both over- and/or under-conservative and more realistic methods need to be developed.

7. Comfort appraisal

In order to appraise comfort for the bridge users, the previously obtained accelerations (from the stochastic pedestrian load model and [3]) should be compared against human tolerance to vibrations. However, defining human tolerance to vibrations is a complex and highly subjective issue that differs among individuals. According to [14] even the same person may react differently to the same vibration on different days indicating the importance of the physiological factor. Moreover, human posture, bridge's location and appearance, surrounding environment, height above the ground as well as previous experience of the users are critical factors for vibrations' perception [15]. Nevertheless, [3] has set vertical and lateral acceleration limits for defining universal comfort levels for all users. These levels have been implemented in the present work to appraise comfort.

From the stochastic pedestrian load model, peak vertical and lateral accelerations fall in the range of medium to minimum comfort depending on the pedestrian density (see Figure 17 and 18). Interestingly, consideration of SLE although increases both vertical and lateral peak accelerations, yields to the same comfort level for the bridge users.

Accelerations predicted by [3] fall in the minimum comfort level for low and medium pedestrian densities. However, for high densities, accelerations become unrealistically high making the bridge response unacceptable. On the other hand, in the lateral direction [3] considers response acceptable whereas in reality significant accelerations occur.

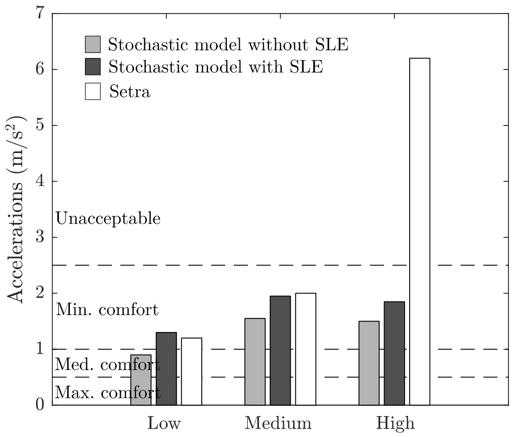

Figure 17. Comfort appraisal in vertical direction.

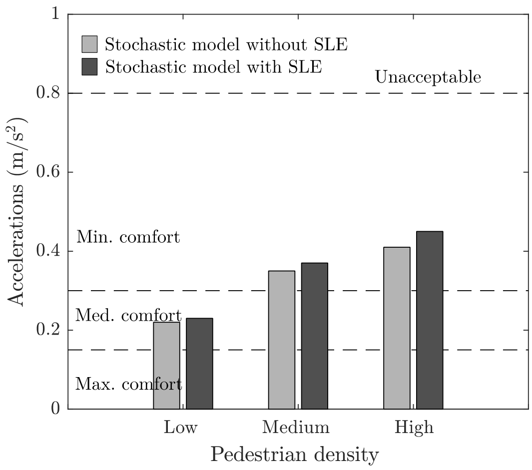

Figure 18. Comfort appraisal in lateral direction.

8. Discussion and conclusions

The dynamic response of a benchmark UDCS footbridge has been investigated in detail. A stochastic pedestrian load model has been applied and the effects of SLE have been examined. Accelerations predicted by current design guidelines have been obtained and compared with that of the stochastic model. Both approaches have been evaluated against proposed comfort limits. The main conclusion are:

- Assessing comfort only considering peak accelerations may be over conservative as these occur in a small area and fraction of the simulation time, and perceived by a very small percentage of pedestrians. Therefore, the use of RMS_{1sec} may be more appropriate for assessing comfort.
- Pedestrians' synchronisation with first torsional mode T1 can increase acceleration response but does not lead to dynamic instability.
- Current design guidelines for predicting accelerations can be both over- and/or under- conservative and therefore more accurate approaches are required.

As the examined UDCS bridge experience high accelerations that can compromise users' comfort, an ongoing research is carried out by the authors aiming to identify critical design parameters that can improve its dynamic response.

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